# Numerical Weather Prediction

## Short-period precipitation forecasts: report from the Mesoscale 'Tiger Team' Project

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by

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## Abstract

Implementation of 'New Dynamics' (ND) in the UK Mesoscale Model in August 2002 led to a detriment in short-period rainfall forecasts relative to the previous operational configuration. This report describes work done by the 'Mesoscale Tiger Team' to investigate the problem and find solutions.

The main focus was on optimising the Latent Heat Nudging (LHN) assimilation of rainfall data for ND, and investigating whether any components of ND had affected its performance. A reduction in the relaxation coefficient for LHN was found to be beneficial in the cases tested, along with a slight modification to one aspect of the LHN algorithm. There was no indication that the new convection scheme with CAPE closure and Convective Momentum Transport, instead of local buoyancy closure, had improved or degraded the signal from LHN.

The set of 12 case studies used as a basis for the investigation yielded some puzzling results, in that rainfall forecasts for ND were actually better than those from Old Dynamics runs, contrary to pre-operational trials. Also, the impact of LHN was detrimental on average for this sample, contrary to expectation from previous studies. These features raise a question mark over the general validity of the LHN tuning, though two features of the results support the value of the tuning. Firstly, where LHN was detrimental, the tuning improved most forecasts, while in cases where LHN was beneficial, the tuning gave a neutral signal. Also, operational performance of the mesoscale model improved relative to the global model after the tuning was implemented, an advantage that had been lost when ND was introduced. A further extended impact trial of LHN in ND would be worthwhile.

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# 1. Introduction

## 1.1 Background to Mesoscale 'Tiger Team'

Objective verification scores for cloud and rainfall forecasts from the UK Mesoscale Model (Mes) have shown little apparent improvement over the last few years (Figure 1). Also, cases are reported, especially in summertime, when the Mes rainfall forecasts are misleading, occasionally for high profile events in the public eye. In addition there have been problems with model spin-up in the first 6 hours or so of the forecast. A deficit in analysed cloud cover is one of the signatures of this problem (see section 4 of Macpherson et al., 2002). Taken together, these issues prompted a desire for small interdisciplinary teams to work on these related problems in a co-ordinated way, so as to improve our forecasts of these key variables. This is the 'Tiger Team' concept.

With the introduction of New Dynamics (ND) to the Mes (Wilson et al., 2004), it was timely to review the status of these problems in the new configuration. After consultation with forecasters, the broad aim of the 'Tiger Team' was modified to tackle more immediate problems with Mes ND forecasts, still with a focus on cloud and rainfall.

The two main problems tackled were short-period rainfall skill, described in this report, and cloud top height assignment. The latter was not a new problem but seemed to be causing particular concern in summer and autumn 2002, with outbreaks of spurious shower generation by misplaced cloud tops. Work in this area led to a new cloud top height scheme being introduced into the Nimrod nowcasting system in March 2003 (Moseley, 2003).

## 1.2 Detriment in short period rainfall skill with Mes ND

As noted by Wilson et al. (2004), implementation of New Dynamics (ND) in the Mes led to a detriment in short-period rainfall skill. This was assigned a high priority by forecasters in autumn 2002. Figures 2 and 3 illustrate the problem. Figure 2 shows the Equitable Threat Score (ETS) against forecast time, for the 6-hour precipitation accumulation with Old Dynamics (OD) and ND. The results are from a pre-operational ND trial that ran from 6 December 2001 to 18 March 2002. The detriment is particularly pronounced in the early part of the forecast and decreases until both Old and New Dynamics achieve a similar score at longer forecast times, when the forecast is influenced more by the boundary conditions than the assimilated observations. Better rainfall forecast skill relative to the global model (Figure 3a) has been a notable feature of the UK Mes model. However, Figure 3b shows a reversal in the relative performance after ND became operational, which raised concern and brought the problem to the main focus of the Tiger Team.

In order to decide a suitable strategy to tackle the problem, it was important to identify possible reasons that led to it. As the detriment appeared in the early part of the forecast, it was evidently related to assimilation. This report provides an assessment of the contribution of rainfall data assimilation to the problem. The rainfall assimilation method had performed beneficially in the context of OD (Jones and Macpherson, 1997, Anderson et al., 2000, Macpherson, 2001 and Anderson, 2002). However, its setup may have needed to be revised for ND. There were also changes in physics and in particular in the convection scheme that may have had an impact on the performance of rainfall assimilation. Finally, the change in the dynamics itself may have influenced the

assimilation performance and may explain to some extent the detriment in early precipitation forecasts.

## 2. Assimilation of rainfall and cloud data in the UK Mes model

Assimilation of rainfall and cloud data in the UK Mes is not part of 3D-VAR, the main assimilation system (Lorenc *et al.* 2000, Macpherson et al., 2002), but is performed with its predecessor, the Analysis Correction (AC) scheme (Lorenc *et al.* 1991). The rainfall component of the AC scheme utilises a simple Latent Heat Nudging (LHN) method (Jones and Macpherson 1997), which assumes that the precipitation rate is proportional to the latent heating rate, as little moisture is stored in clouds. LHN then uses the ratio of the observed to model precipitation rate to scale the vertically integrated latent heating rate, by adding temperature and moisture increments that are consistent with this scaling. For the assimilation of cloud data, a simple relationship is used to convert input cloud fraction to relative humidity and the model relative humidity is then nudged toward that value. The input to the AC scheme comes from the Moisture Observation Preprocessing System (MOPS, Macpherson *et al.* 1996), which consists of a 3-dimensional cloud analysis with information from surface and satellite observations and also surface precipitation rate estimates from the radar analysis of Nimrod, the Met Office nowcasting system (Golding 1998).

## 3. Case study experiments

The approach employed to investigate the detriment in early forecast precipitation and develop solutions to the problem was to run suites of assimilation – forecast cycles for 12 cases that included a wide range of weather types (Table 1). The case studies cover the period August 2001 – May 2002. Each suite started from a reconfigured OD (UM vn4.5) global analysis and ran through 24 hours of mesoscale assimilation cycle, producing two 24-hour forecasts at 00 UTC and 12 UTC. The experiments were run with UM 5.2, VAR 19.1 and OPS 12.1. Experiments with OD were run with UM 4.5, VAR 18.5 and OPS 11.11. The same set of case studies was used for the December 2002 and March 2003 Mes assimilation upgrades (Renshaw et al., 2004). The latter included changes from the Mes Tiger Team work presented here. The availability of the case studies for immediate use by the Tiger Team was certainly an advantage. However, a more appropriate approach aimed at improving rainfall skill, would be to only use cases with significant rain events. A larger number of experiments would also lead to a more reliable verification of the results, but in practice the number of experiments is always subject to time and computational cost constraints.

The experiments that were carried out with the case studies are summarised in Table 2 and can be classified into 4 categories according to their purpose:

- reference experiments without and with MOPS assimilation (Exp 1-3)
- optimising LHN tuning for ND (Exp 4-11)
- investigating the impact of changes in the convection scheme (Exp 12-14)
- investigating the impact of changes in dynamics (Exp 15-17)

Table 3 provides a comparison of rainfall skill scores for various pairs of experiments. These results will be explained in more detail in the next section.

## 4. Results

### 4.1 Optimising LHN for ND

Four different approaches were investigated as possible ways of optimising LHN for ND. Their impact on rainfall forecasts was assessed mainly by objective verification, though some individual cases were examined subjectively in more detail. Retuning of LHN was attempted by:

1) reducing the LHN weight
2) repositioning the AC scheme within the Unified Model timestep
3) changing the correction of precipitation errors
4) modifying the smoothing of LHN increments

Results from the above approaches are presented below.

*Reducing the LHN weight*

Early testing of ND revealed that MOPS cloud data received too high a weight in the AC scheme, resulting in a detriment in rainfall forecasts. Halving the weight, i.e. applying a relaxation coefficient of 0.5 to the computed increments at each timestep, gave an improvement in rainfall forecast, whilst retaining the benefit in cloud cover forecasts (Renshaw et al., 2004). However, the assimilation of MOPS data in ND continued to have a negative impact on rainfall forecast skill. The Tiger Team work focused on the LHN component of the AC scheme. Following the work on cloud data, a reduction in the weight given to MOPS rainfall data seemed a likely candidate for further improvement in early precipitation scores.

Table 3 shows that LHN on its own (LHN vs. NOAC) gave a detriment in precipitation, whereas the inclusion of cloud assimilation (ALLMOPS vs. LHN) gave a smaller and mixed signal. When half-weight LHN was used, the precipitation skill increased (LHNhalf vs. LHN) in both blocks 00 (whole model area) and 03 (all UK stations). Although the reduced weight brought a benefit compared to the full weight (1.5-2% increase in rainfall ETS), it still was unable to recover a positive impact from MOPS rainfall data on early precipitation forecasts (LHNhalf vs. NOAC). This is illustrated in Figure 4 which depicts the change in ETS when MOPS rainfall data were assimilated with full and half weight in LHN. The detriment with half weight was clearly smaller than the full weight, but the sign of the change in ETS remained negative.

With a sample of only 24 forecasts from 12 cases, one has to be cautious about the general validity of signals in skill from particular changes. To help assess the merit of the tuning, a more detailed look was taken at the distribution of tuning impacts amongst the cases. Figure 5 illustrates the partitioning of the benefit and the detriment from the new LHN tuning between a number of precipitation forecasts. The reduced weight was found to improve most bad cases with a negative LHN impact, while it had a roughly neutral effect on the cases of LHN benefit, which suggests that there is some true benefit from the retuning.

Cases where LHN had a significant impact were examined individually and two examples of subjective verification are shown in Figures 6 and 7 for cases b (clear summer day) and d (land gales). These were the cases for which LHN gave the most positive and the most negative signal. Figure 6 illustrates how the benefit for case b appeared on the forecast

and shows the LHN and NOAC analysis for the 12Z forecast, together with the radar image at the same time. The AC scheme began to insert LHN increments 2 hours before the analysis time, so the effect of LHN already shows in the results. Moreover, if the system had formed at earlier times, then the results would also have influence of earlier assimilation cycles. The benefit from LHN is quite striking in this case, as the run without assimilation of MOPS rainfall completely missed the rain band in the north of the UK. The advantage of employing LHN was also evident in the first 2-3 hours of the forecast and could account for the skill score increase in the objective verification.

Figure 7 corresponds to the 12Z forecast of case d, for which LHN was found to bring the highest detriment. Both NOAC and LHN experiments represented the observed rain well at the analysis time, though LHN generated more rain in the first 3 hours of the forecast. Therefore, the detriment in the skill was probably not related to the position of the rain band, but its intensity. Standard objective verification computes the precipitation skill score using data from rain gauges, which apparently indicated less rain intensity for this case, or closer agreement with the NOAC run. However, comparing the analysis with the radar image in Figure 7 did not give a clear indication whether NOAC actually provided a more accurate representation of rainfall. This underlines the need to incorporate verification against radar into the standard procedure of assessing precipitation forecasts.

*Repositioning the AC scheme in the UM timestep*

The introduction of semi-Lagrangian advection in ND may have influenced the performance of the AC scheme. Within an ND timestep, the AC scheme is called after the physics and before the Helmholtz solver. The solver was not part of the OD timestep. Moving the AC scheme after the solver would not allow the solver to respond directly to its increments and may thus retain more information from the assimilation of MOPS data. On the other hand, this approach may prove more damaging to the forecasts, since the model would enter the next timestep without its fields being as well balanced as in the original positioning. An experiment was conducted to test the net effect of the above factors. In experiment ALLMOPSsolver, the 12 case studies were run with the AC scheme called after the solver. Comparison with ALLMOPS (Table 3) indicated that the proposed rearrangement of the call to AC within the UM code is detrimental to early rainfall forecasts and should therefore be avoided.

*Changing the correction of precipitation errors*

Experiment modLHN1 tested a detail of the LHN algorithm. In LHN, the algorithm scales the model latent heating profile by the ratio of the observed to the model rainfall at that point. However, the vertical profile might be unrepresentative of the real vertical structure if the precipitation ratio is too large. Currently a limit of 3 is imposed. If this is exceeded, then the algorithm checks the neighbouring grid points for a better match with the observed rainfall at the first gridpoint. If one is found, then the vertical structure from there is used instead to derive the LHN increments at the original point. Details are in Jones and Macpherson (1997). ND may be less forgiving of errors in the vertical structure of the LHN increments and this was tested by reducing the maximum factor of disagreement with the model from 3 to 2 in modLHN1. The results in Table 3 show that the change had a small, but positive impact in both blocks 00 and 03 (+0.1-1% improvement in rainfall ETS).

*Modifying the smoothing of LHN increments*

LHN produces temperature and humidity increments that display small scale features and subsequently applies filtering to produce smooth increment fields, as the fine details are unlikely to give a meaningful representation of rainfall errors on small scales and may instead generate gravity waves. Figures 8a and 8c show an example of theta increments from LHN with and without smoothing. It is evident that even though the broad patterns look similar, the local features may be quite different, both in sign and in magnitude. Increments without smoothing show higher extreme values, which are also confined to smaller areas.

Experiment modLHN2 attempted a new smoothing method, whereby filtering was not applied to the output increment fields, but to the input precipitation fields (observed and model background), from which the LHN increments are calculated. This approach allows more of the small scale features to be retained (Figure 8b) and was used as a sensitivity test to investigate their impact on rainfall forecasts. Experiment modLHN3 ran the case studies without any filtering. Figure 9 shows the rms LHN temperature increment profile for various cases. Standard filtering yielded the lowest rms values at all model levels, whereas the new filtering was closer to the run without increment smoothing. The red line in Figure 9 gives an estimate of the rms increment values that correspond to the model latent heating change in the first timestep (uncorrected by LHN) and demonstrates that the assimilation method did not introduce changes that are unrealistically large with respect to changes due to model evolution in the same period. Another test for the increment smoothing was provided by experiment allLHNcomb, which applied the new smoothing to the input LHN fields, but also a final filtering to the LHN increments with a larger filter scale (35km instead of 21km).

Results from the various tests are summarised in Table 3, which measures the impact of the changes on the early precipitation accumulation ETS. The new smoothing tested with modLHN (modLHN2 vs. LHN) had only a small impact (less than 0.5% change in rainfall ETS) with different sign in blocks 00 and 03. When compared against runs with no filtering (modLHN2 vs. modLHN3), it was found to give an improvement in block 00, but a small detriment in block 03. When the final smoothing was also applied, for runs with both MOPS components, the early precipitation forecast for the composite of the 12 case studies improved (allLHNcomb vs. ALLMOPS), especially in block 03 (1.2% increase in the ETS).

In conclusion, smoothing seems to be necessary in order to optimise LHN performance, though its impact is small and not systematically positive. However, a more thorough assessment would also require subjective verification of forecasts, to determine whether there may be cases for which different filtering options can have a noticeable effect on rainfall patterns.

*Revising the LHN tuning*

The Mes Tiger Team investigated several possible ways of optimising the performance of LHN, in order to improve the skill in early rainfall forecasts. A summary of the effect of each test when compared to runs without MOPS assimilation is illustrated in Figure 10. The results are again for the composite of the 12 case studies. For all cases, MOPS assimilation led to a detriment in the skill. However, in some cases the skill improved

relative to runs with OD AC settings (ALLMOPSfull and LHNfull) and also relative to runs with the initial settings for ND but with reduced cloud weights (ALLMOPS and LHN). The most significant gain was achieved in experiments with reduced LHN weights. The change in the correction of precipitation errors was also found to give a clear, though smaller, benefit. On the other hand, changing the position of the AC scheme in the code was detrimental to the forecast skill. The sign of the other changes that were investigated was ambiguous, though there is an indication that better smoothing of the LHN input and output may result in some improvement in the rainfall ETS. On the basis of the above results, the revised LHN weight and precipitation correction settings were incorporated into the Mes spring 2003 upgrade package, which led to a significant improvement in operational short-period forecasts, as discussed later.

## 4.2 Changes in the convection scheme

Transition from Old to New Dynamics was accompanied by a number of improved parametrizations (Wilson et al., 2004). Of all the changes in model physics, it was the new convection scheme that seemed likely to have some effect on the performance of LHN, as it alters the model convective rainfall, which is one input to LHN. For example, if the new scheme improved the modelled convective rain significantly, then the MOPS data may have a lesser impact on rainfall forecasts, at least for convective precipitation.

The new convection scheme for ND (Gregory *et al*. 1999) has an improved closure to determine the initial mass flux and also includes a convective momentum transport (CMT) switch. In OD the initial plume mass flux was computed empirically from the stability of the lowest convective layers (local buoyancy closure), whereas in ND an alternative closure is employed, based on the Convective Available Potential Energy (CAPE). The CMT switch also allows momentum transport in the vertical in addition to heat and moisture transport.

*Impact of convection changes on rainfall forecasts*

A number of experiments were carried out to test the impact of the new convective scheme on rainfall forecasts. Table 3 shows the change in weighted ETS for comparisons between runs with the old and the new scheme. Experiment NOACnoCAPE ran the case studies with the old closure and no MOPS assimilation, to identify any benefit or detriment from the new scheme on its own. The changes in the ND convective parametrization were found to bring a detriment in the rainfall ETS (NOAC vs. NOACnoCAPE), though its magnitude is too small to have statistical significance. When MOPS rainfall assimilation was also included in runs without CMT, or with the whole of the old scheme (experiments LHNnoCMT and LHNnoCAPE), it was found that OD convection options gave a mixed signal, negative but small in block 00 (whole model area) and positive in block 03 (UK area).

Objective verification for the composite of the 12 case studies is by no means a rigorous test for the new scheme, as only 3 of the case studies actually have significant convective incidents (cases a, f and l). These cases were investigated individually and results are shown in Figure 11. The three cases gave very different results, implying that the changes in convection can sometimes be positive and sometimes negative in terms of early precipitation forecast skill. It is evident that a much larger number of cases with convective rain is required to form any definite conclusions about the impact of the new

scheme, though it looks almost certain that the impact is too small to account for the detriment in early rainfall forecasts investigated by the Mes Tiger Team.

*Impact of convection changes on the signal from LHN*

A way to assess the performance of LHN under the new and the old convection scheme, was to produce a scatter plot (Figure 12), where each point corresponds to a t+6 forecast from the 12 case studies and the axes measure the ETS change for runs with and without LHN, for the old scheme (x-axis) and the new scheme (y-axis). The statistics included three thresholds of precipitation accumulation (0.2, 1 and 4mm). Points above the diagonal line in Figure 12 correspond to cases where CAPE/CMT gave a better change in ETS from LHN and hence improved the early precipitation with respect to local buoyancy closure and no CMT, whereas the opposite holds for points below the line. Apart from some extreme points on both sides, the convection scheme seemed to have hardly any effect on the LHN performance, though the composite statistics showed a small benefit from the old convective scheme, which should be more obvious in block 03 (Table 3, LHNnoCAPE vs. NOACnoCAPE for the old scheme and LHN vs. NOAC for ND). Of course, most of the forecasts on the scatter plot correspond to weather conditions for which the convective scheme should have a null average effect. Therefore, any trends shown in the results, with only a few significant convective cases present, can not be deemed as reliable indicators. It is also interesting to note that most of the points on the scatter plot lie below the horizontal dotted line and to the left of the vertical dotted line, which illustrates the detriment in forecast skill with MOPS rainfall assimilation, both with CAPE and local buoyancy closure.

## 4.3 Changes in Dynamics

In the course of the Mes Tiger Team work, it became evident that more comprehensive investigations would require rerunning the 12 case studies with OD. This would provide a straightforward way to measure the effect of dynamics on rainfall forecasts and would be expected to confirm the detriment in the early precipitation forecast skill seen in pre-operational trials. It would furthermore provide a measure of the LHN impact on the forecast, which in OD was found to be positive, whereas after the implementation of ND its sign seemed to have reversed. The results from runs with OD were in many ways surprising and contrary to expectation. Table 3 gives a brief summary of results from various tests, described below in more detail.

Figures 13 and 14 depict the rainfall ETS against forecast time in blocks 00 (whole model) and 03 (UK) respectively. In all cases, either with, or without assimilation of MOPS data, ND significantly improved the rainfall forecast skill, especially so for the T+6 forecasts (also evident in the last four entries in Table 3). This of course contrasts with the findings of the ND pre-operational trial, illustrated in Figure 2, which highlighted the problem of early precipitation detriment and concentrated much of the Tiger Team effort on developing solutions to it. Figure 15 gives the OD vs. ND comparison for each of the 12 case studies. For the majority of the cases ND was found to perform significantly better than OD. It is only case k (stratocumulus) that showed a considerable improvement with OD, but only in block 03; for the whole Mes area the effect was the opposite. Another point to note is that when the cloud part of MOPS was included, which may be quite important for this particular case, the contrast between OD and ND in the two blocks reduced.

A way to assess the performance of MOPS in ND against OD is again with the aid of a scatter plot (Figure 16), which shows the ALLMOPSfull vs. NOAC change in ETS for t+6 forecasts from the 12 case studies with OD (y axis) and ND (x axis). Full weights were used for both rain and cloud in MOPS, as was the case for OD. It is clear that for this particular investigation, MOPS was more beneficial in OD than ND for block00, as more points lie above the diagonal line. The benefit was less evident in block 03.

The next step was to test how the revised tuning of MOPS with reduced cloud and LHN weights changed these results. The new scatter plots are shown in Figure 17. MOPS assimilation was now found to give a better signal in ND than in OD for block 03, with more points below the diagonal, though for block 00 the results were close to neutral. However, this improved signal actually corresponds to a smaller detriment from LHN in these cases. The same conclusions illustrated with the scatter plots can also be reached by examining the composite statistics in Table 3.

So far it is the impact of both cloud and rainfall assimilation on precipitation forecasts that has been tested. The next step is to separate the cloud component and see its relative effect in Old and New Dynamics. Figure 18 shows the change in rainfall and cloud ETS when the cloud component of MOPS is added to LHN. Adding the cloud component resulted in a detriment in rainfall ETS, which was considerably smaller in ND. In fact the reduced LHN weight managed to even change the sign of the impact from cloud data in block 03. The assimilation of clouds generally seemed to improve cloud forecasts and increased the total cloud amount ETS, as would be expected. The OD results are very sensitive to the observations used and there was a marked change in both the sign and the magnitude of the ETS difference in blocks 00 and 03. Finally, the change in MOPS weights in ND did not alter the results very much.

The results from OD experiments summarised in this section did not accord with expectation, either for the precipitation skill relative to ND, or for the LHN impact on rainfall forecasts. Unless there was some unknown error in the course of the experiments, the above inconsistencies are not easy to explain. All the experiments carried out in this study, with or without MOPS assimilation, suggested an improvement in rainfall ETS with ND, contrary to the ND pre-operational trial. These new results may simply indicate that the case study sample used here can not give a good representation of long term trends and may thus need to be supplemented with more cases, or altogether replaced by better ones. Alternatively, if these results reflect indeed a better performance of ND, then a marked improvement must have occurred in ND since its original implementation, for which, however, there is not sufficient evidence. Assimilation of MOPS rainfall led to a detriment in the case composite rainfall ETS also in OD, even though previous studies demonstrated the merits of using LHN (Macpherson 2001, Anderson 2002). Subjective verification of individual cases investigated here showed a clear benefit from LHN for forecasts with a higher skill score relative to a control without rainfall assimilation, whereas for forecasts with a poorer skill score, the LHN run still managed to represent the rain patterns well. This may be indicative of a deficiency in the objective assessment of rainfall. Verification against radar may prove to be more reliable and should be considered in future developments.

## 5. Conclusions

The detriment in the short period rainfall forecast with ND was a main focus of the Mes Tiger Team. A strategy was developed to provide solutions, as well as identify where the problem stems from, with a number of experiments which used a set of 24 forecasts from 12 case studies. The experiments investigated ways of optimising LHN in ND and tested the effect of changes in physics and dynamics on rainfall assimilation. The results were assessed primarily in terms of objective 6-hour rainfall verification. The main points from this work are listed below.

 Reducing the LHN weight, like the previous retuning of MOPS cloud weight, proved a very efficient way to optimise LHN in ND. Experiments with reduced LHN weight increased the early rainfall ETS significantly (Figure 4). Although this retuning seemed to constrain the forecast detriment significantly, it still didn't manage to reverse the LHN impact and get a positive effect from MOPS rainfall assimilation.

A question that arises is whether the improvement with the reduced weight is simply a consequence of the fact that the use of MOPS rainfall data is detrimental to rainfall forecasts. If that is the case, then reducing the weight to the data would of course be beneficial, but omitting them altogether would be the best solution. Such a view, however, is not well justified for the following reasons:

1) When evaluating the impact of the reduced weight separately for instances of detriment and benefit from LHN (Figure 5), it was found that the reduced forcing improved most of the negative cases, while having a neutral impact on the positive ones. This suggests that the tuning did more than just damping the signal from data in all circumstances.
2) OD runs for the set of case studies employed here yielded lower rainfall scores than the equivalent ND runs and were not indicative of the expected benefit from LHN. Therefore, if LHN indeed brings an overall benefit, as demonstrated for OD (Macpherson 2001, Anderson 2000), and half weight introduces a further improvement, as suggested by the current results, then LHN is likely to perform better in the context of ND, but more work would be needed to demonstrate whether this is a valid assumption.

 Imposing stricter constraints on the correction of precipitation errors in the LHN scheme also proved beneficial to the forecast, though its impact was about an order of magnitude smaller in terms of the ETS. This change, together with the reduced LHN weight, was part of the Mes upgrade in spring 2003 (Renshaw et al., 2004).

 Retaining the small scale features in the LHN increments by filtering the input to the scheme but not its output increments, had a neutral impact on the forecast. There was a suggestion that smoothing both the input and the output with a larger filter scale might have a small advantage, but more cases are required to demonstrate any benefit from a revised smoothing.

 Using the new convection scheme with CAPE closure and CMT, instead of local buoyancy closure, gave no definite indication of improvement or detriment in rainfall forecasts. The assessment of the scheme with the 12 case studies measured the impact on general weather situations, whereas more convective cases are necessary for more rigorous testing. A few individual convective cases that were examined here gave a mixed

signal. The above investigations imply that any significant change in the rainfall forecast skill cannot be attributed to the change in the convective scheme.

 The set of 12 case studies could not demonstrate the early precipitation detriment with the change in dynamics, but on the contrary showed a significant improvement in the 6-hour rainfall ETS (about 10-15% increase), with or without assimilation of MOPS data. Furthermore, the impact of LHN on its own was negative even in OD, which also disagrees with expectation from previous work. If the assimilation of rainfall has remained beneficial in ND, then the revised tuning of LHN is expected to make the assimilation even more efficient.

 Assimilation of cloud data showed a detriment in rainfall skill, but generally an improvement in cloud amount forecast skill. The rainfall detriment was more pronounced with OD, whereas the revised weights in both components of MOPS with ND seemed to have the potential to eliminate the detriment, whilst retaining the benefit in cloud forecasts.

The operational implementation of the LHN optimisation changes that were suggested in this work was indeed followed by an anticipated positive impact on early rainfall forecasts, measured by skill relative to the global model. This is illustrated in Figure 19, which comes from a 3-month period of operational running with the new LHN settings and shows the rainfall ETS against forecast time. Further monitoring of the operational runs showed that this positive signal persisted also for the period July-September 2003. On the evidence of these results, the Mes Tiger Team seems to have achieved its short term objectives, by restoring the model to its previous relative performance standards.

It would be more satisfying to deal with the unresolved issue of the LHN impact in ND with a longer investigation so that continuing benefit from rainfall assimilation could be clearly demonstrated. This work showed that a limited set of case studies is unable to provide a clear indication of the overall LHN impact. Therefore, a more comprehensive study would require a continuous trial, long enough to provide a statistically significant rainfall verification score.

In the longer term, based on experiences elsewhere, improvement in short-period rainfall forecasts will no doubt emerge from developments in 4DVar, though whether the computational cost will be reasonable enough for operational use remains to be seen.

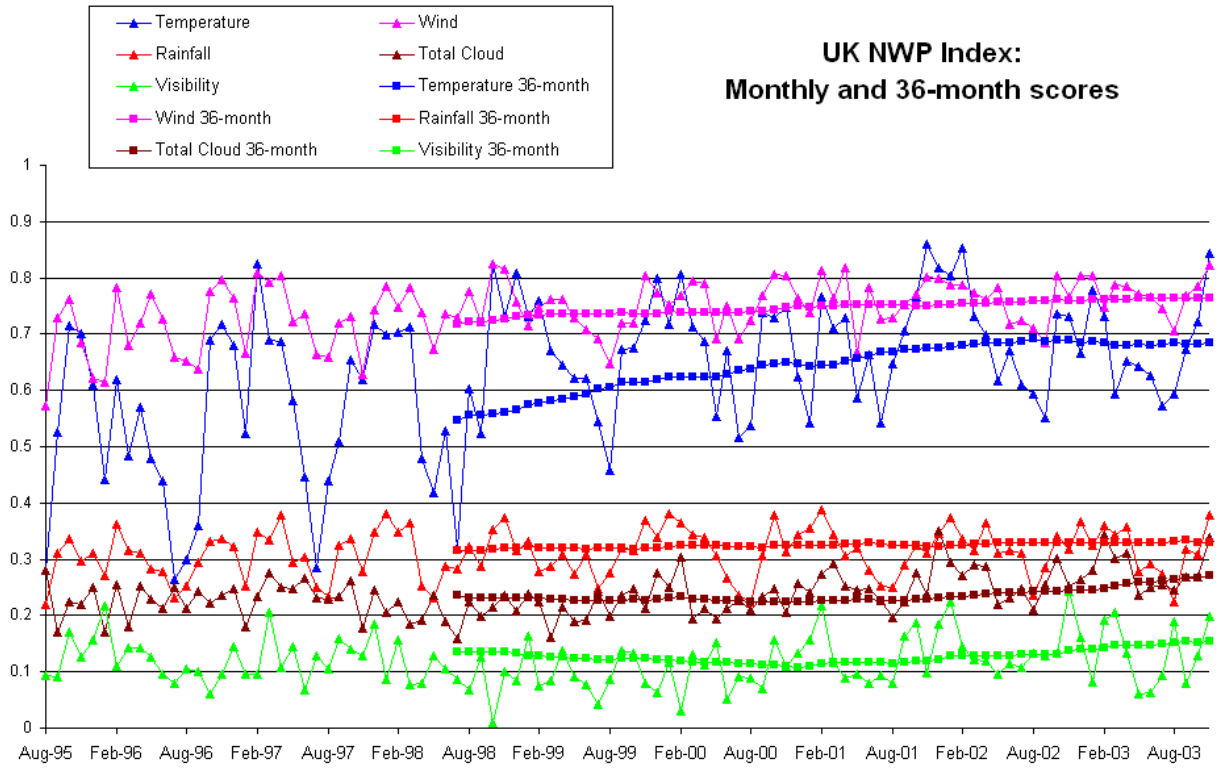


**Figure 1**: Time series of monthly and 36-month average skill scores for the components of the UK Mesoscale NWP index. Note especially the lack of trend in the score for rainfall (red), while that for cloud cover (brown) is roughly level until around early 2002.

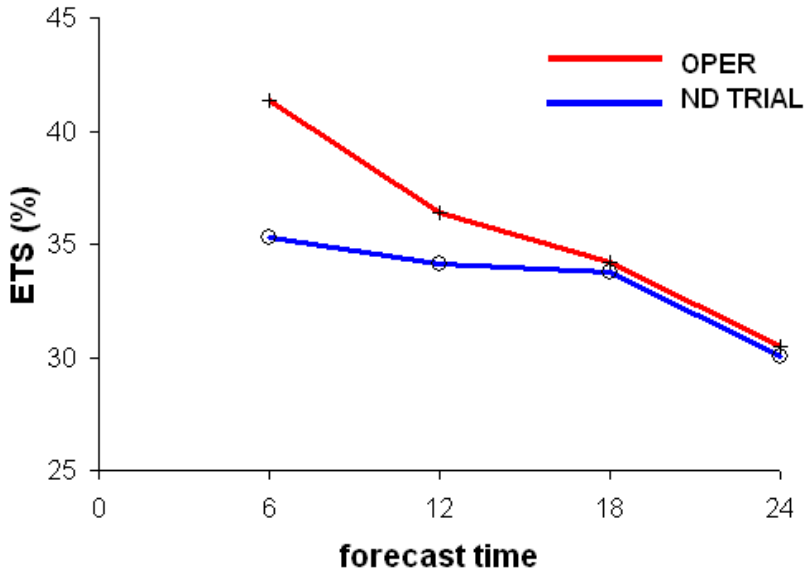


**Figure 2** Results from a New Dynamics (ND) pre-operational trial (6 December 2001 - 18 March 2002) for the 6-hour precipitation accumulation ETS in the whole model area (block 00) with operational OD (red line) and ND (blue line). The ETS values are averaged over three thresholds (0.2, 1.0 and 4.0 mm/6hr). Forecasts verified against surface observations

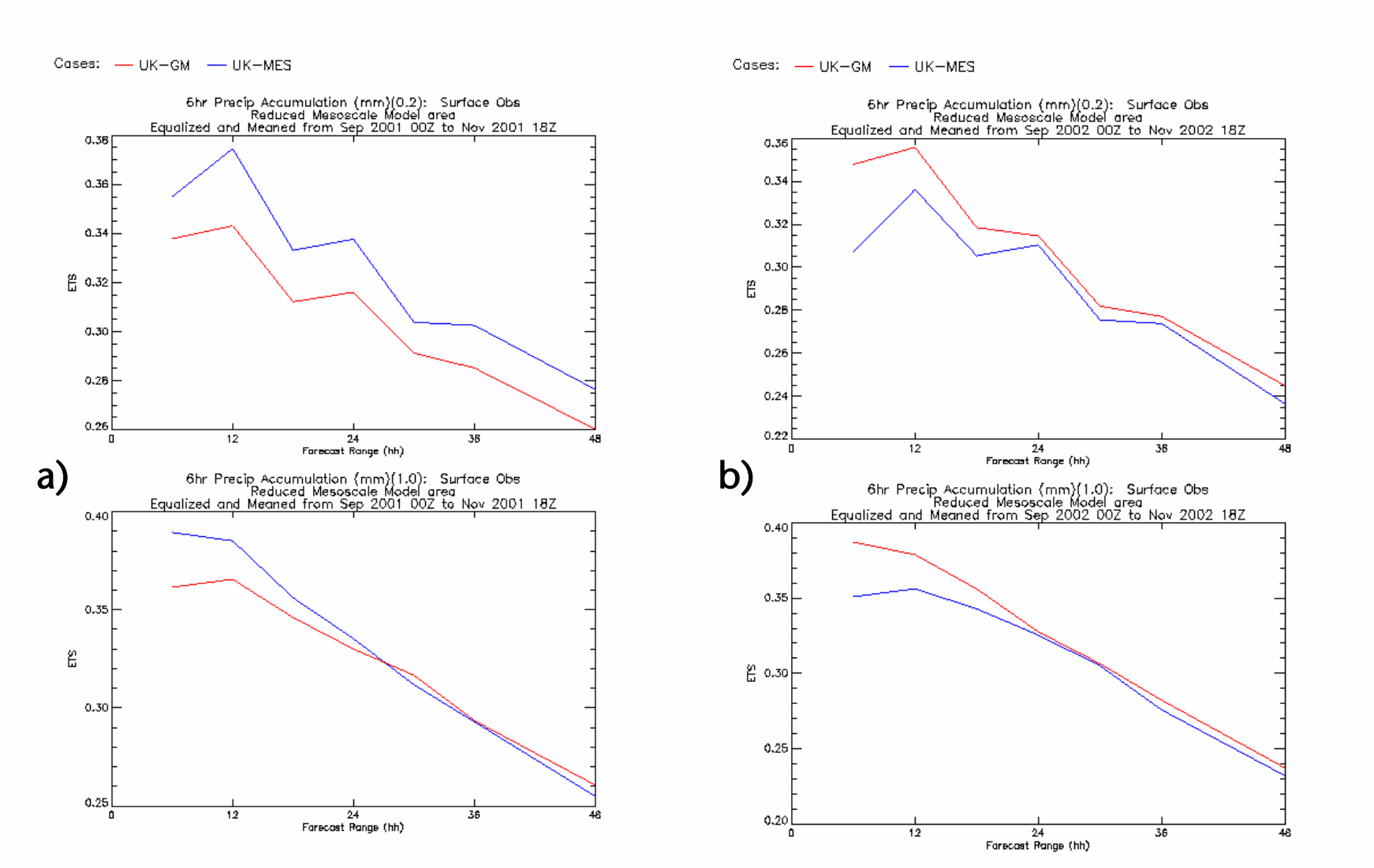


**Figure 3** a) The 6-hour precipitation ETS against forecast time for the global (red line) and the UK Mes model (blue line) at a threshold of 0.2 (top) and 1mm/6hr (bottom) for the period Sep-Nov 2001 (OD). b) The same for the period Sep-Nov 2002 (ND). Forecasts verified against surface observations

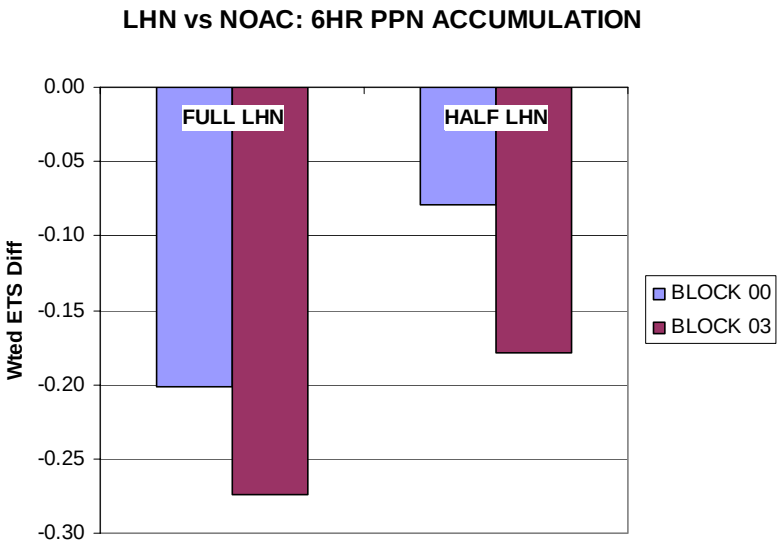


**Figure 4** The change in the Weighted ETS rainfall skill score when rainfall assimilation is included, for full and half weights in LHN and blocks 00 (whole model area) and 03 (UK and Ireland stations only). The 'Weighted ETS change' is 20 times the absolute ETS change, a scaling that enters the calculation of the composite UK NWP index. A weighted ETS change of 0.2 represents typically around 3% of the absolute ETS score.

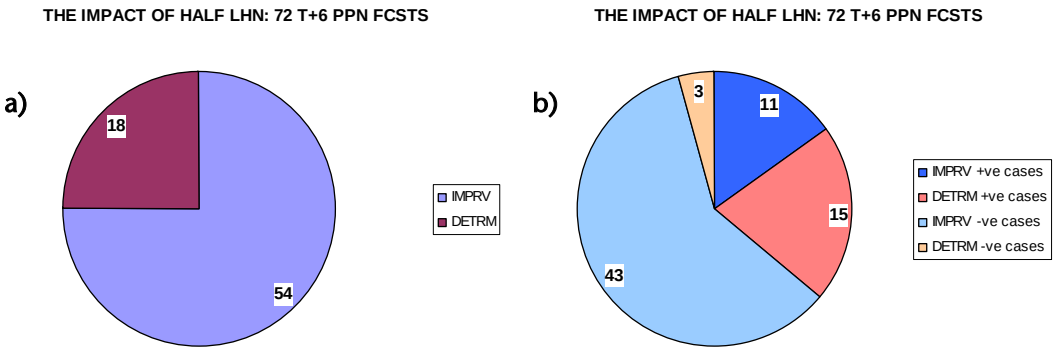


**Figure 5** An assessment of the impact of reduced LHN weight on the 6-hour precipitation accumulation ETS for 24 forecasts at 3 rainfall thresholds:
a) the impact on the ETS when the LHN weight is halved – detriments are red and improvements are blue
(b) the impact on the ETS among cases where full-weight LHN gave a positive signal and cases where it gave a negative signal. Cases with LHN detriment that were improved are light blue, while cases of LHN detriment that were made worse are yellow. Cases of LHN benefit made worse are light red and cases of LHN benefit that were improved are dark blue.

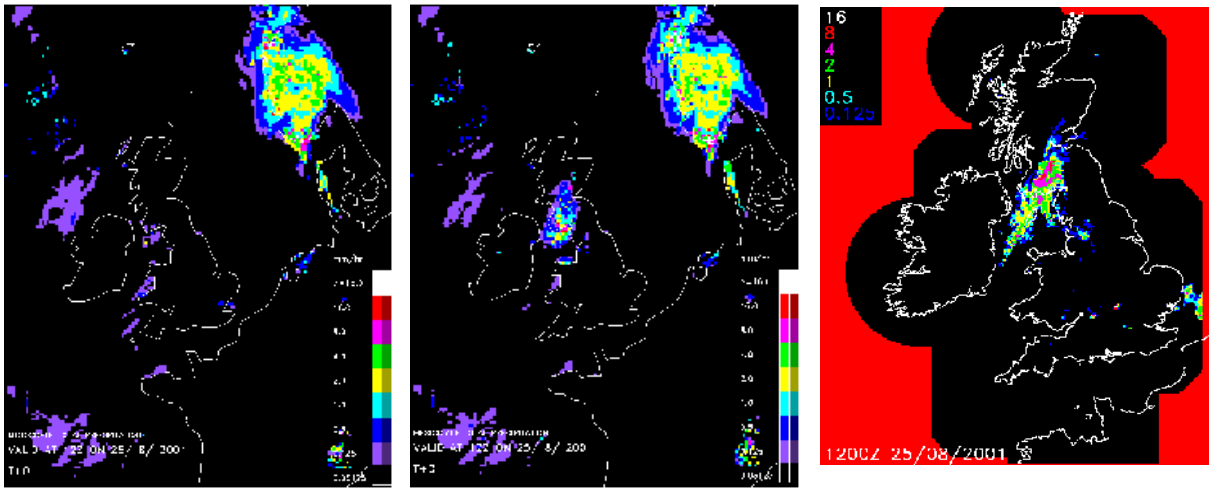


**Figure 6** Subjective rainfall verification for the analysis at 12Z for case b. Results from run NOAC (left) and run LHN (middle) and the radar image at the same time (right)

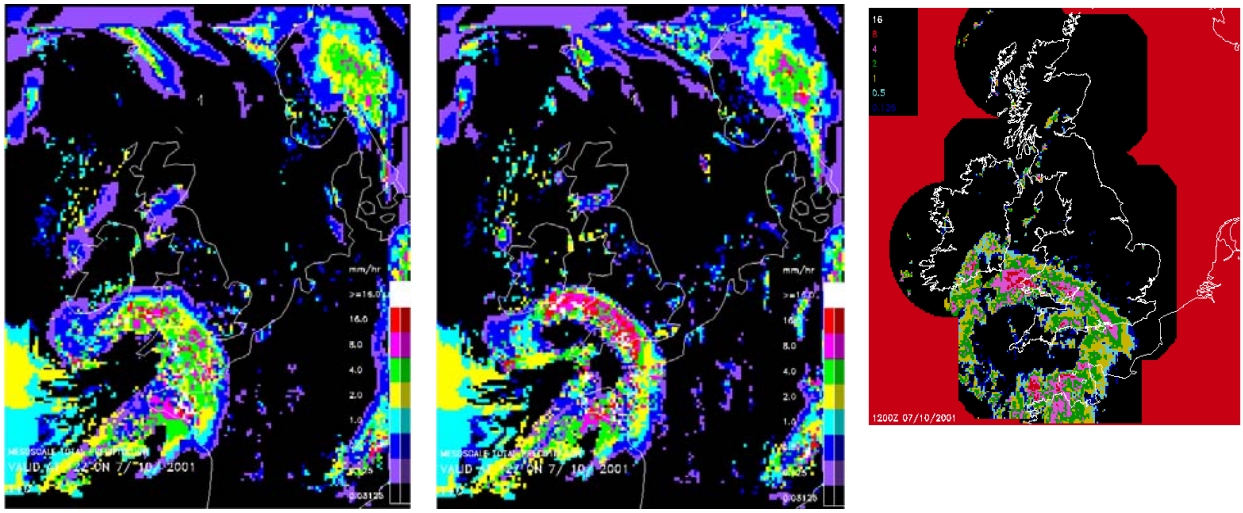


**Figure 7** Subjective rainfall verification for the analysis at 12Z for case d. Results from run NOAC (left) and run LHN (middle) and the radar image at the same time (right)

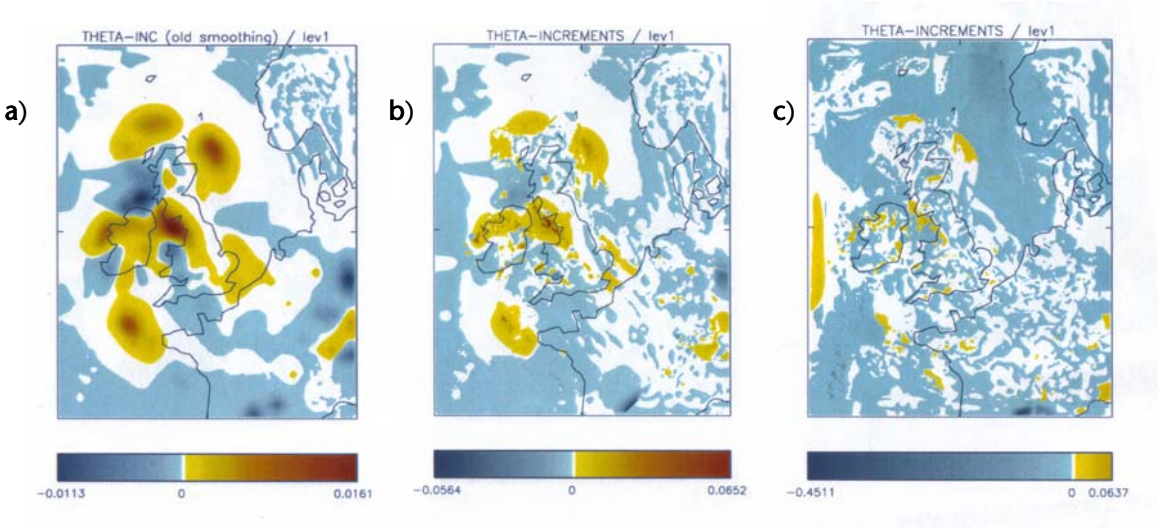


**Figure 8** Theta increments on model level 1 produced from a difference between two 1-timestep model runs with and without LHN. The fields give a representation of LHN increments, as the model changes at the end of the first timestep are the same for the two runs and the difference comes only from the assimilation. The results are for runs starting on 23 Dec 2003 / 4Z a) with standard increment filtering, b) with the new filtering and c) without filtering

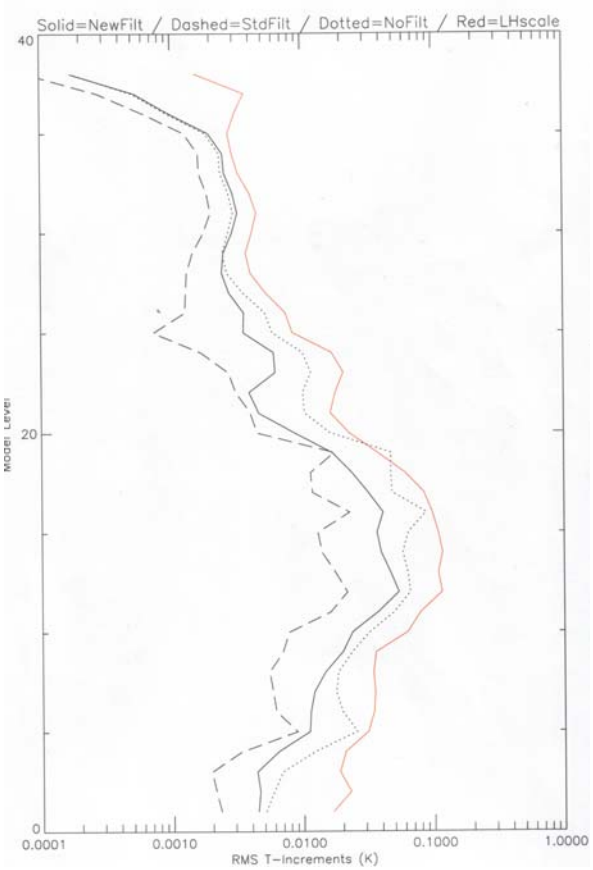


**Figure 9** The rms temperature increment profiles from LHN (black lines) for the cases with the new filtering (solid line), standard filtering (dashed line) and no filtering (dotted line). The red line shows the model's latent heating change in one timestep

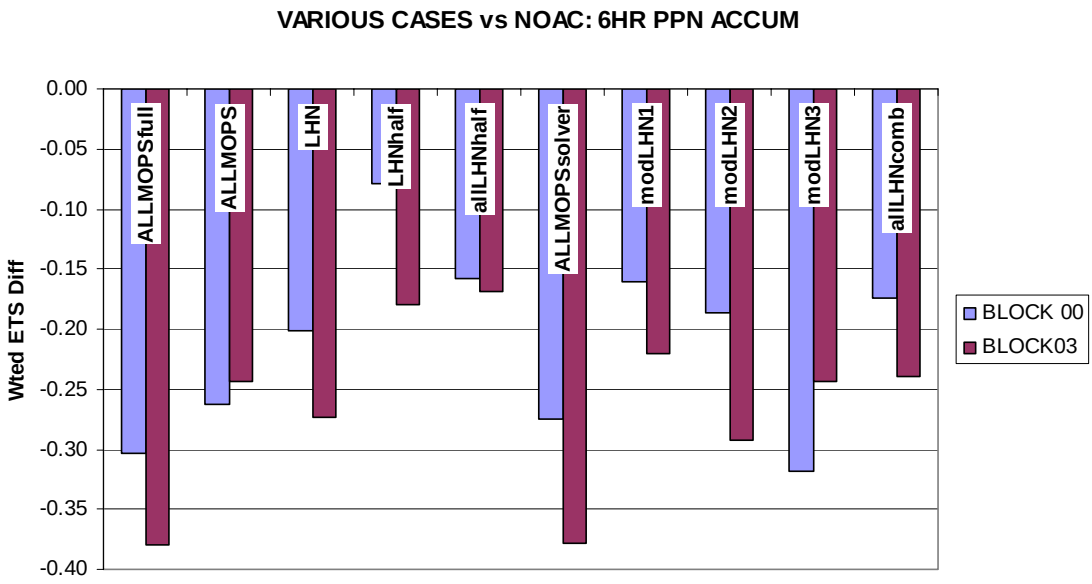


**Figure 10** The change in the Wted ETS rainfall skill score in several experiments relative to experiment NOAC. The skill is computed for the composite of the 12 case studies in blocks 00 (whole model area) and 03 (UK and Ireland).

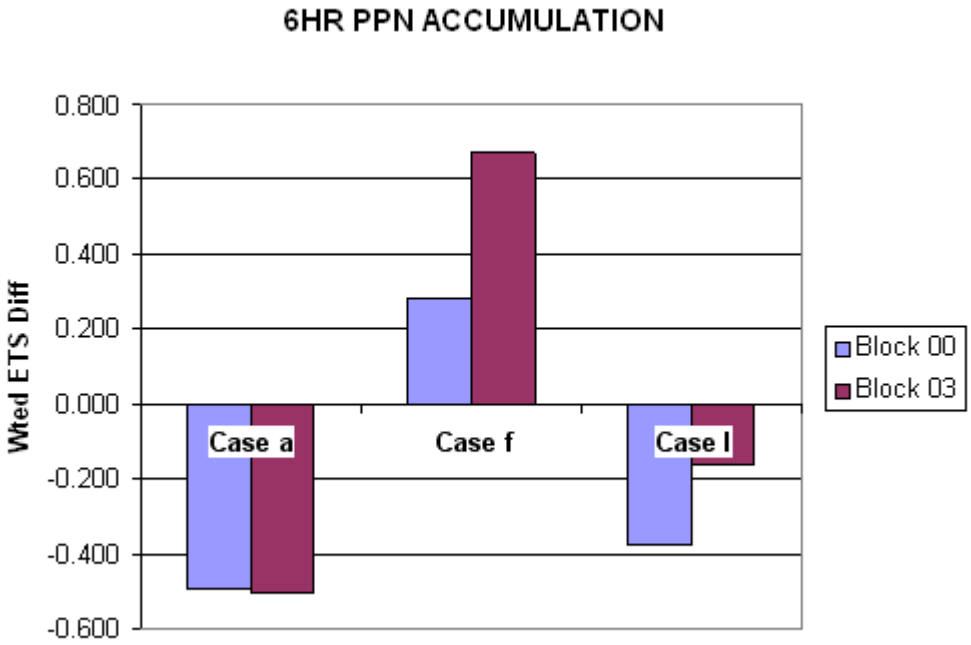


**Figure11** The change in Wted ETS rainfall skill score for 3 case studies with convective rain incidents, for a comparison between runs with the old scheme relative to runs with the new convection scheme. LHN was included in all experiments

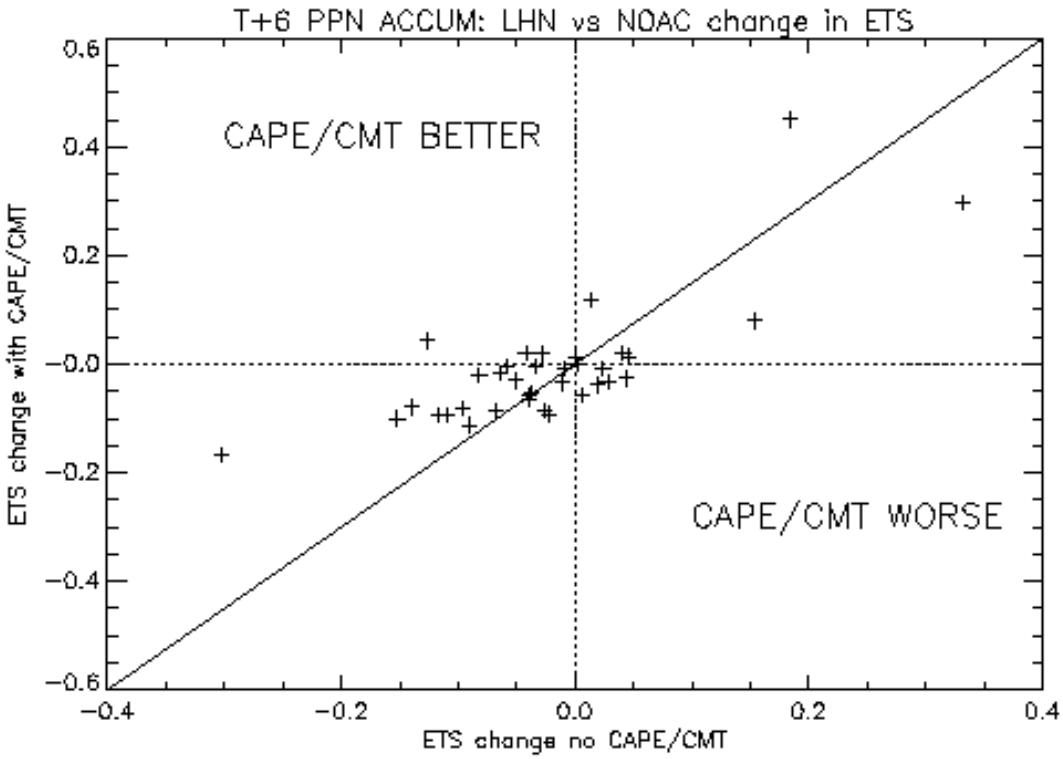


**Figure 12** The impact of LHN on 6-hour precipitation accumulation ETS with the old (local buoyancy closure) on the x-axis and the new (CAPE closure & CMT) convection scheme on the y-axis, for block 00. The crosses (+) correspond to t+6 forecasts from the 12 case studies used in the Mes Tiger Team investigations

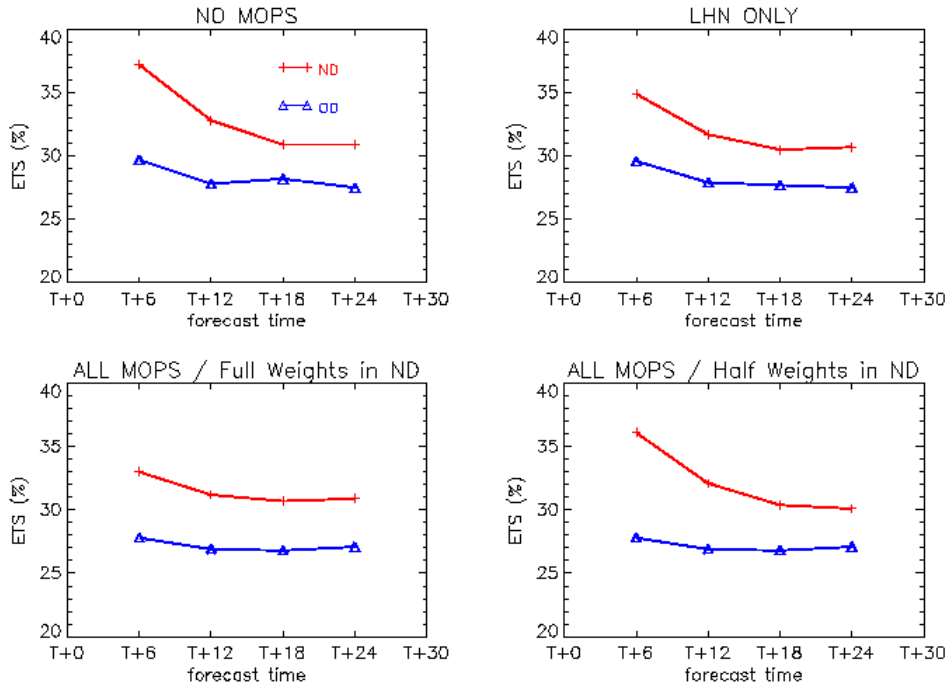


**Figure 13** 6-hour precipitation accumulation ETS in block 00 with ND (red line) and OD (blue line) for the composite of the 12 case studies in experiments without MOPS assimilation (top left), with LHN only (top right), with both components of MOPS and either full (bottom left) or half (bottom right) weights in ND. The ETS values are averaged over three thresholds (0.2, 1.0 and 4.0 mm/6hr).

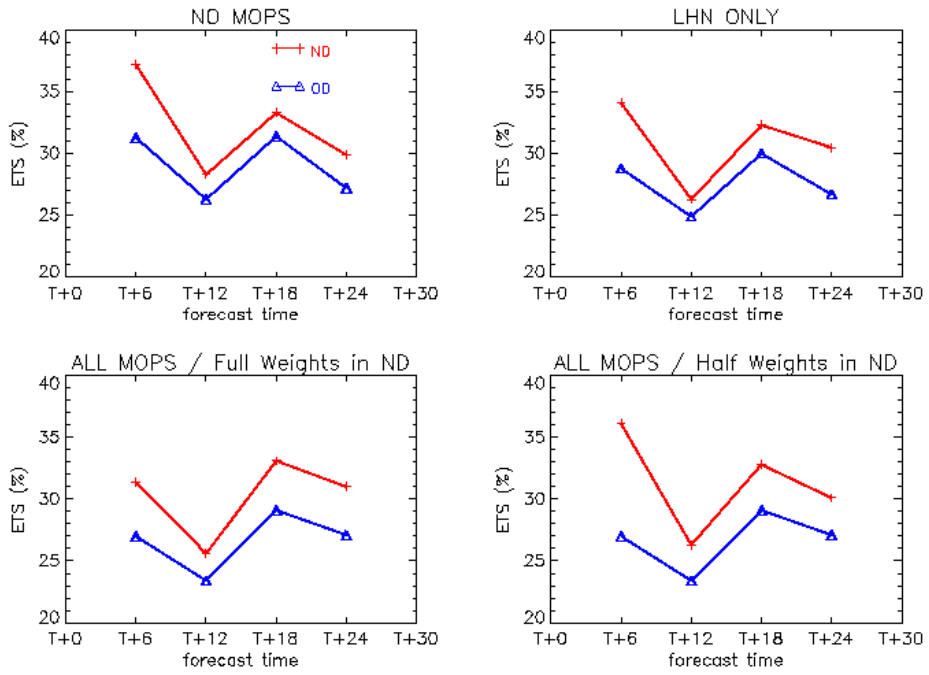


**Figure 14** The same as Figure 13 for block03

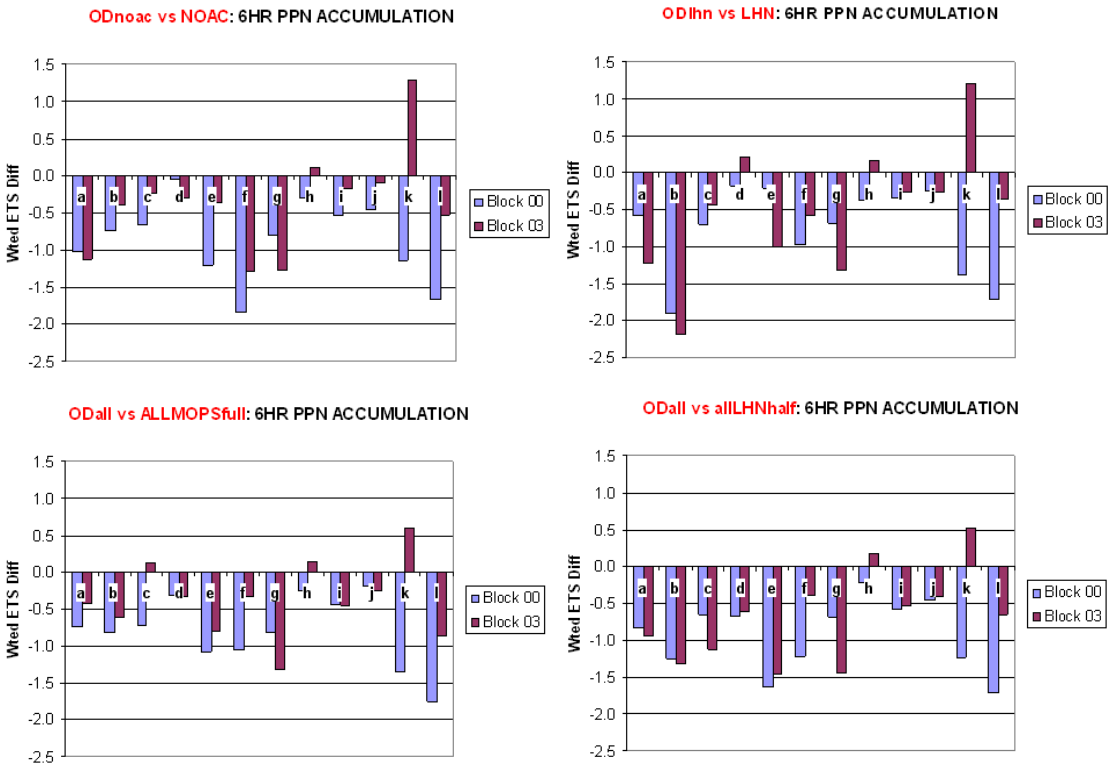


**Figure 15** The change in Wted ETS rainfall skill score for OD relative to ND for the 12 case studies and different experiments, without and with MOPS components

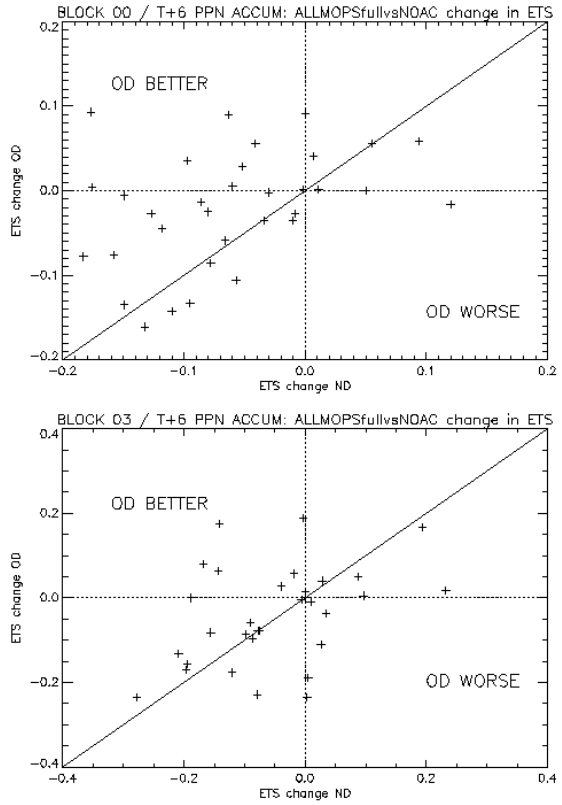


**Figure 16** The change in 6-hour precipitation accumulation ETS in ND (x-axis) and OD (y-axis) due to MOPS assimilation with full weights for block 00 (top) and block 03 (bottom). The crosses (+) correspond to t+6 forecasts from the 12 case studies

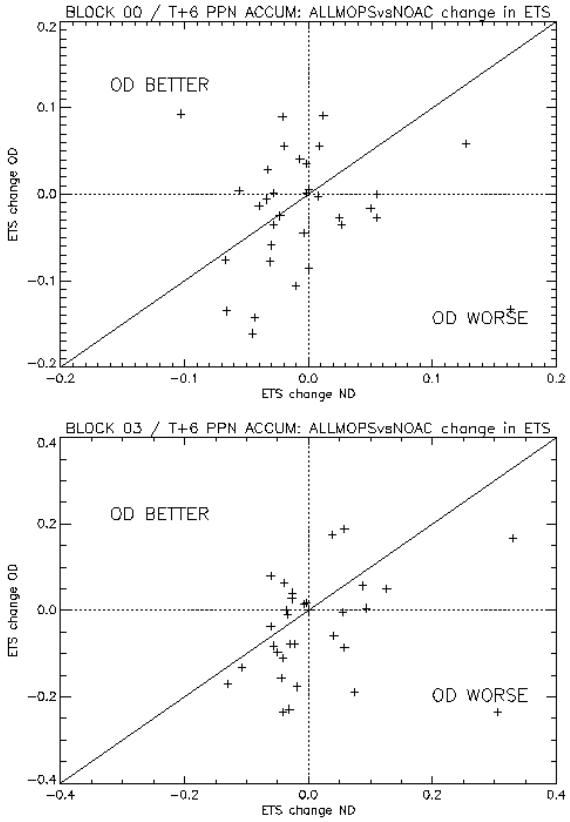


**Figure 17** Same as Figure 16, but with half cloud and LHN weight in MOPS assimilation

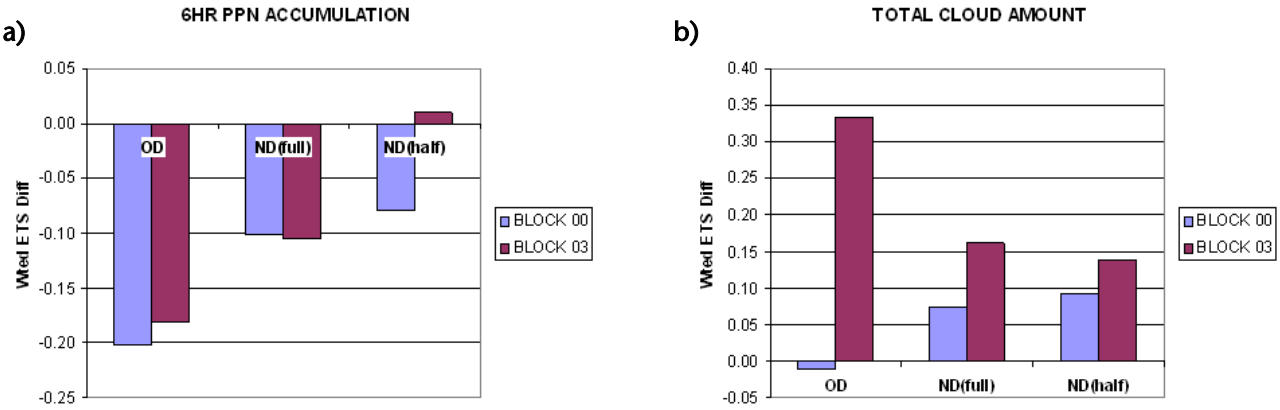


**Figure 18** The change in the (a) 6-hour rainfall and (b) cloud weighted ETS in blocks 00 and 03 for OD, ND and full weights in MOPS, and ND and half weights in MOPS. The change is due to the addition of the cloud assimilation in experiments with MOPS rainfall assimilation (cloud +rain vs. rain only)

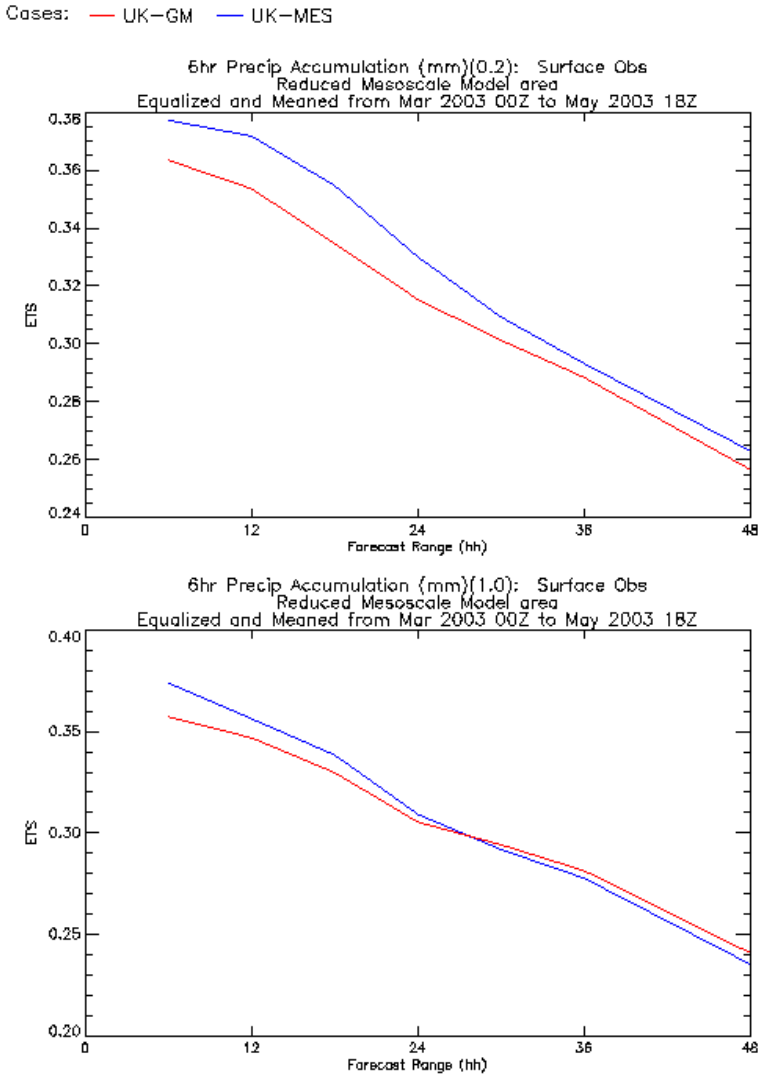


**Figure 19** The 6-hour precipitation ETS against forecast time for the global (red line) and the UK Mes model (blue line) at a threshold of 0.2 (top) and 1mm/6hr (bottom) for the period Mar-May 2003, with revised LHN tuning operational since March 18th.

**Table 1.** A summary of the 12 case studies

| Case | 1st Forecast | 2nd Forecast | Description |
|---|---|---|---|
| a | 040801 12Z | 050801 00Z | Organised convection (summer) |
| b | 250801 12Z | 260801 00Z | Clear summer day |
| c | 220901 12Z | 230901 00Z | Radiation fog |
| d | 071001 00Z | 071001 12Z | Land gales |
| e | 141001 00Z | 141001 12Z | Radiation fog |
| f | 231001 12Z | 241001 00Z | Organised convection (winter) |
| g | 281201 00Z | 281201 12Z | Mixed snow and rain |
| h | 311201 00Z | 311201 12Z | Clear winter night |
| i | 250102 00Z | 250102 12Z | Air mass (active) front |
| j | 270102 00Z | 270102 12Z | Stratus |
| k | 030302 00Z | 030302 12Z | Stratocumulus |
| l | 020502 00Z | 020502 12Z | Convection-diurnal, local heating, land-based |

**Table 2.** The experiments carried out with the set of the 12 case studies

| Exp No | Name | Description |
|---|---|---|
| 1 | NOAC | No MOPS assimilation |
| 2 | ALLMOPS | With MOPS assimilation (as after Autumn 2002 upgrade) |
| 3 | ALLMOPSfull | ALLMOPS with full weights (as before Autumn upgrade) |
| 4 | LHN | LHN only (no MOPS clouds) |
| 5 | LHNhalf | LHN only with half weight |
| 6 | allLHNhalf | ALLMOPS with half LHN weight |
| 7 | ALLMOPSsolver | ALLMOPS with AC called after the solver |
| 8 | modLHN1 | LHN with different correction of ppn errors |
| 9 | modLHN2 | LHN with different LHN increment smoothing |
| 10 | modLHN3 | LHN with no LHN increment smoothing |
| 11 | allLHNcomb | ALLMOPS + new smoothing + new final smoothing |
| 12 | NOACnoCAPE | NOAC with local buoyancy closure and no CMT |
| 13 | LHNnoCMT | LHN with CAPE and no CMT |
| 14 | LHNnoCAPE | LHN with local buoyancy closure and no CMT |
| 15 | ODnoac | NOAC with OD |
| 16 | ODlhn | LHN with OD |
| 17 | ODall | ALLMOPSfull with OD |

**Table 3.** 6hr precipitation accumulation weighted ETS difference[1] (Test Exp vs. Control Exp) in blocks 00 and 03 for the composite of the 12 case studies

| | TEST EXP | CONTROL EXP | Wted ETS Difference BLOCK 00 | BLOCK 03 |
|---|---|---|---|---|
| LHN weight | ALLMOPS | NOAC | -0.263 | -0.243 |
| | ALLMOPSfull | NOAC | -0.303 | -0.379 |
| | LHN | NOAC | -0.201 | -0.274 |
| | LHN | ALLMOPS | 0.062 | -0.031 |
| | LHNhalf | LHN | 0.122 | 0.095 |
| | LHNhalf | NOAC | -0.079 | -0.179 |
| | allLHNhalf | NOAC | -0.158 | -0.169 |
| | allLHNhalf | ALLMOPS | 0.106 | 0.075 |
| solver | ALLMOPSsolver | ALLMOPS | -0.012 | -0.135 |
| ppn errors | modLHN1 | LHN | 0.042 | 0.054 |
| filtering | modLHN2 | LHN | 0.015 | -0.019 |
| | modLHN2 | modLHN3 | 0.123 | -0.029 |
| | allLHNcomb | NOAC | -0.174 | -0.240 |
| | allLHNcomb | ALLMOPS | 0.004 | 0.089 |
| convective scheme | LHNnoCMT | LHN | -0.010 | 0.028 |
| | LHNnoCAPE | LHN | -0.005 | 0.196 |
| | LHNnoCAPE | NOACnoCAPE | -0.188 | -0.196 |
| | NOAC | NOACnoCAPE | -0.005 | -0.096 |
| Old Dynamics | ODlhn | ODnoac | -0.024 | -0.293 |
| | ODall | ODnoac | -0.226 | -0.475 |
| | ODnoac | NOAC | -0.985 | -0.582 |
| | ODlhn | LHN | -0.805 | -0.601 |
| | ODall | ALLMOPSfull | -0.901 | -0.673 |
| | ODall | allLHNhalf | -1.064 | -0.893 |

[1] The weighted ETS difference is computed from the sum of twelve 6-hour precipitation accumulation ETS differences (test-control), for forecasts valid at t+6, t+12, t+18 and t+24 and for 3 thresholds (0.2, 1 and 4 mm/6hr). The 'Weighted ETS change' is 20 times the average ETS change in these 12 components.

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